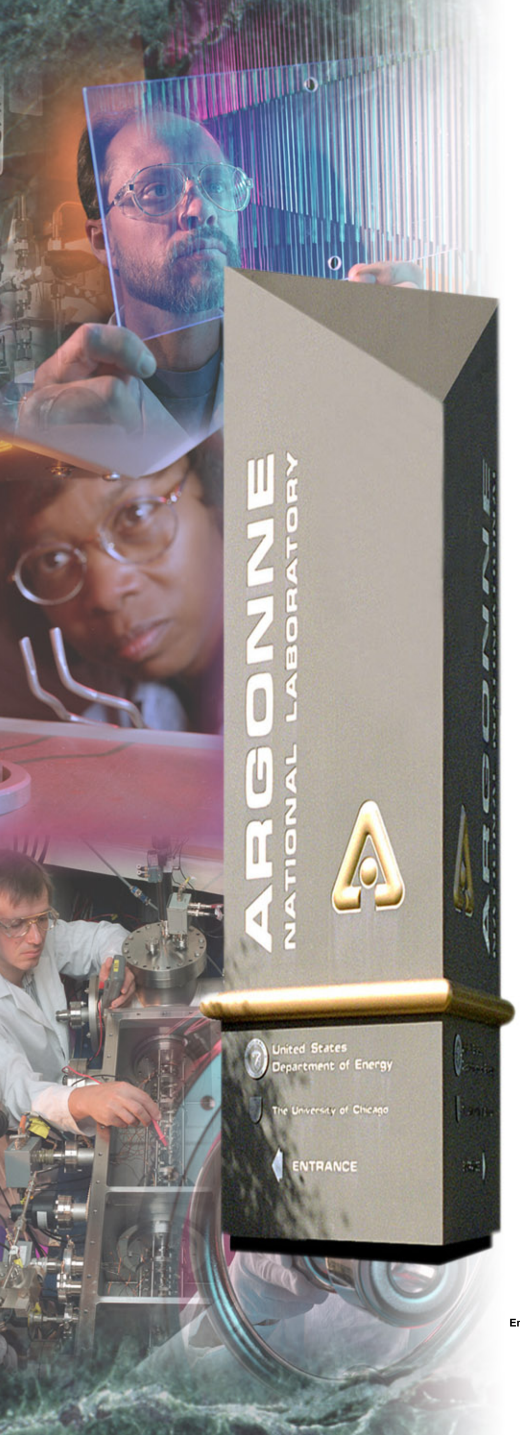

Fabrication of Small-Orifice Fuel Injectors

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Outline

- **Introduction & Background**
  - The Need
  - A Path
  - The Concept
  - The Method
- **Implementation**
- **Application**
- **Conclusions & Further Work**

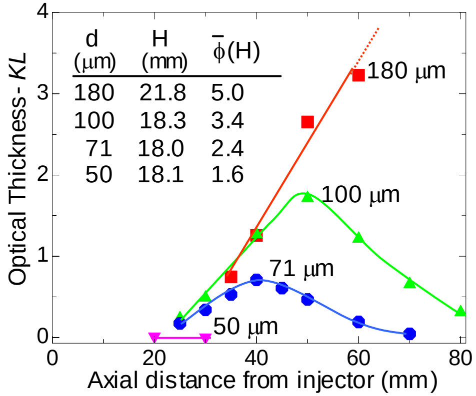
The Need

- **Decrease emissions**
  - 2007 EPA emissions guidelines for diesel engines are quite stringent
  - Further emission reduction mandates are likely
  - Diesel engines are more efficient than SI engines
  - Keeping diesel-powered vehicles on the road thus saves energy
- **Increase fuel efficiency**
  - Unburned fuel and incomplete combustion reduces engine efficiency
  - Improving combustion process will increase efficiency

A Path

- **Many different strategies for reducing emissions are being tried**
  - Aftertreatment devices
  - Changes in engine cycle
  - Changes in injector design
- **EPA: PM emissions from an LD engine reduced by using 75 µm orifice injectors**
- **SNL: PM eliminated in bench tests by reducing injector orifice diameter to 50 µm**

From Pickett, Siebers, Morales, Hachman, and Sinensky, "An Investigation of Diesel Soot Formation Processes Using High Aspect Ratio Micro-Orifices," 2003. Optical thickness KL is indicative of the amount of soot in the fuel jet.

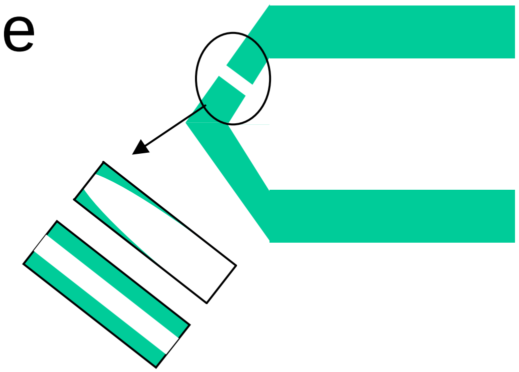


Problems with Small Orifices

- **Decreased fuel delivery**
  - Compensate by increasing injection pressure, number of spray holes, and/or discharge coefficient
- **Sensitivity to plugging**
  - Coking potentially a major issue, especially with alternative fuels such as biodiesel
- **These must be considered**

The Concept

- **Economically fabricating 50 µm-orifice injectors on a commercial scale is currently impossible**
  - Limit for economical EDM fabrication is 100 µm
  - Other technologies (laser drilling, LIGA, etc.) too difficult to scale up
- **Solution: Reduce orifice diameter by coating the ID of a current-technology injector**
  - Wide array of techniques for depositing material
  - Select an appropriate one



The Method

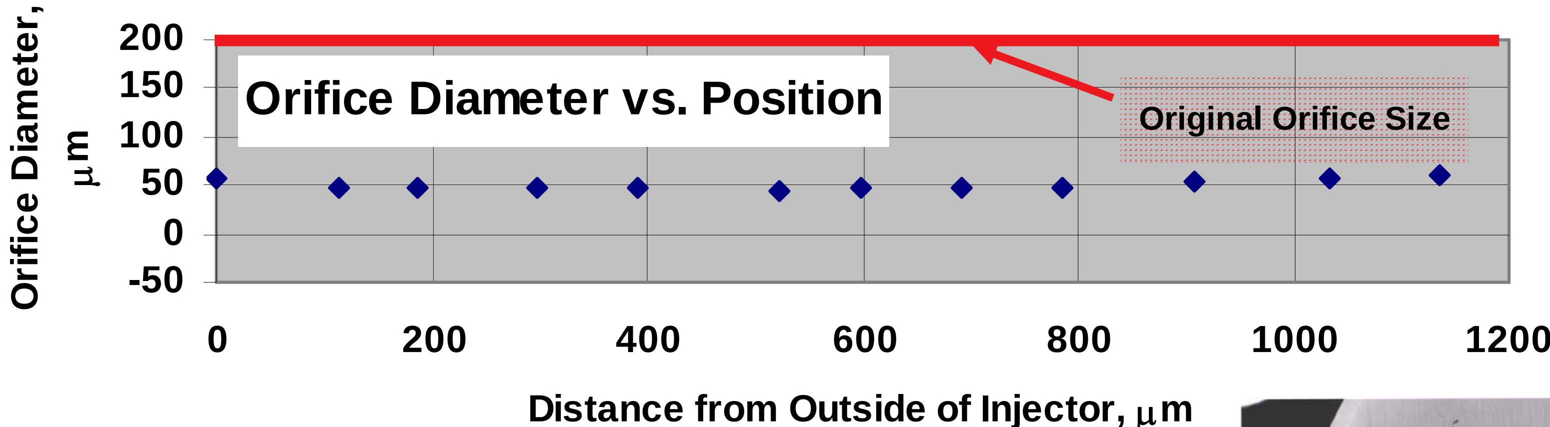
- **After careful examination of the available techniques, we chose Electroless Nickel (EN) plating**
  - Mature technology, inexpensive, widely commercialized
  - Highly conformal coatings of internal surfaces
  - Potential for depositing different alloys to tailor:
    - *Mechanical properties: Erosion resistance*
    - *Chemical properties: Corrosion/Coking resistance*

Potential Issues

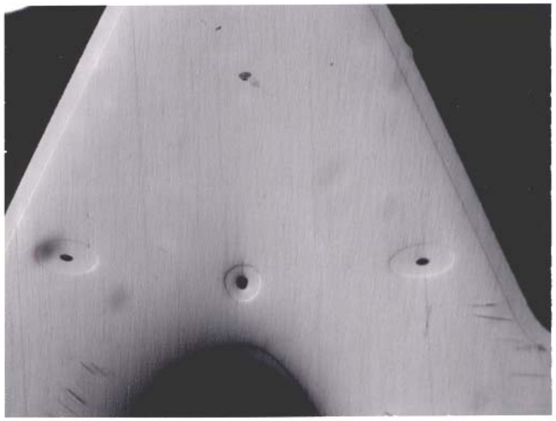
- **Hole size—is diameter reduction to 50 μm possible using EN plating?**
- **Uniformity—does the coating process change the circularity of the holes and/or the needle guide?**
- **Adhesion—will the coating come off in use?**
- **Durability—is the coating capable of resisting the impact loads in the needle seat and the possibility of cavitation erosion in the orifices?**
- **Surface finish—is the coating smooth enough in the as-deposited state, or will further processing be necessary?**

Results: Hole Size & Uniformity

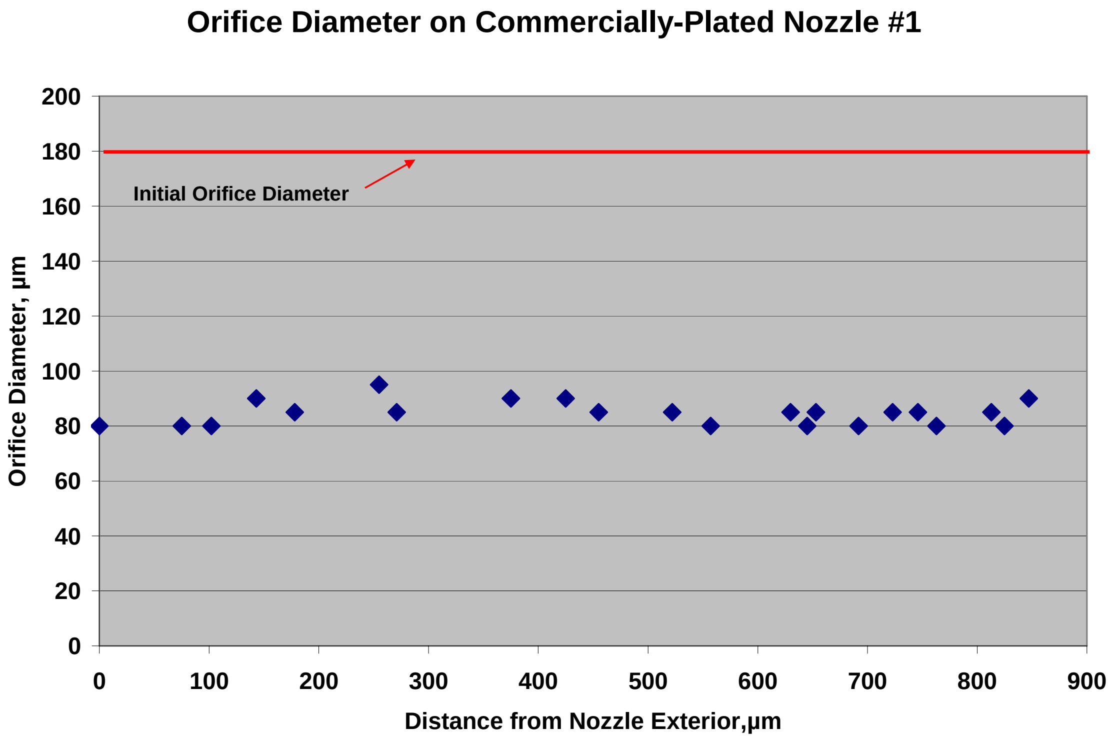
- We have reduced orifice diameter to 50 µm in bench-scale tests, and to 75-80 µm in commercial-scale tests

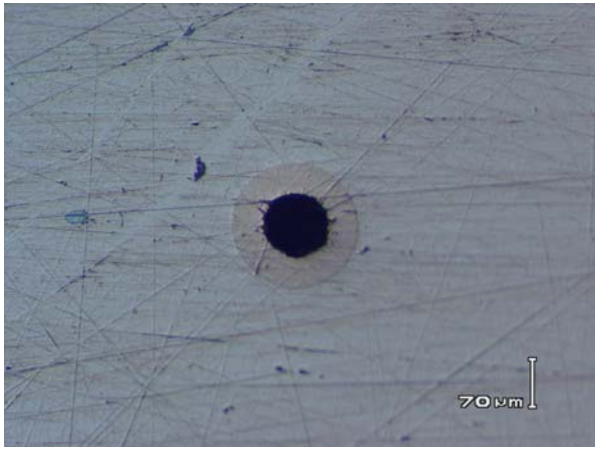


- Circularity and uniformity also appear to be satisfactory



Results: Hole Size & Uniformity (cont'd)



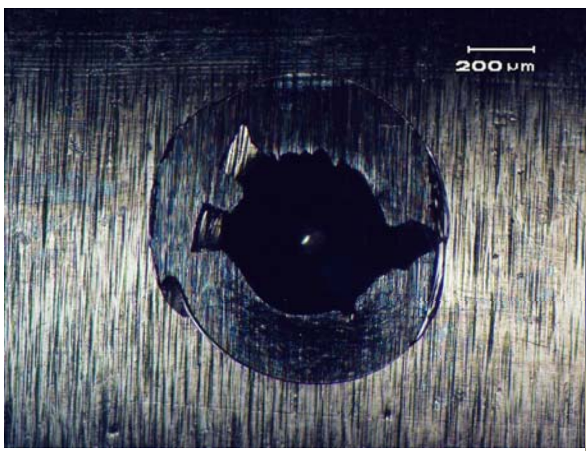


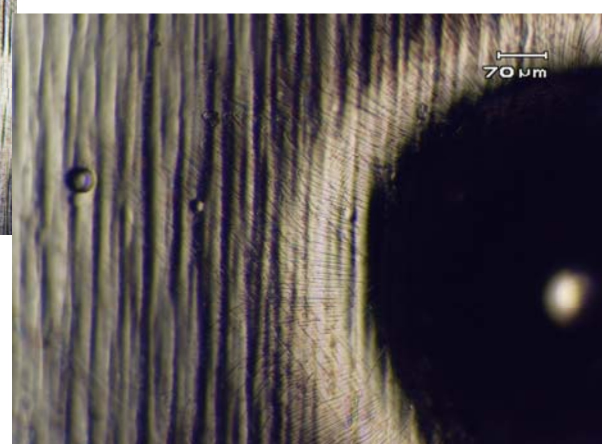
- **Scatter in the diameter is due to a surface finish issue, since resolved**

Results: Adhesion

- **Initially we had problems with adhesion in our bench-scale coatings**
- **Adhesion on the commercial-scale coatings is excellent, as shown by Rockwell indent tests**

Commercial coating





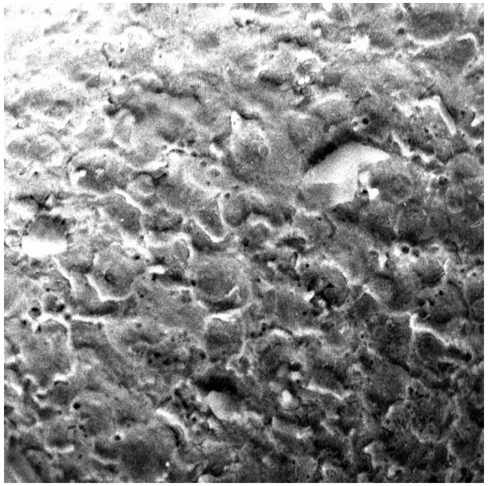
Bench-scale coating

Results: Durability

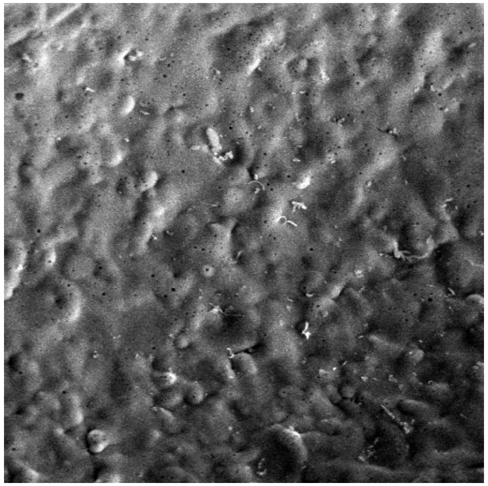
- **In bench-scale tests, coating hardness ranged from HK_{50} 400 to 800, depending on phosphorus level, vs. substrate hardness of ~700.**
- **Softer coatings generally have higher strain-to-failure**
- **We can thus tailor the coating to give optimal durability in use**
- **Impact tests for the needle seat are planned**

Results: Surface Finish

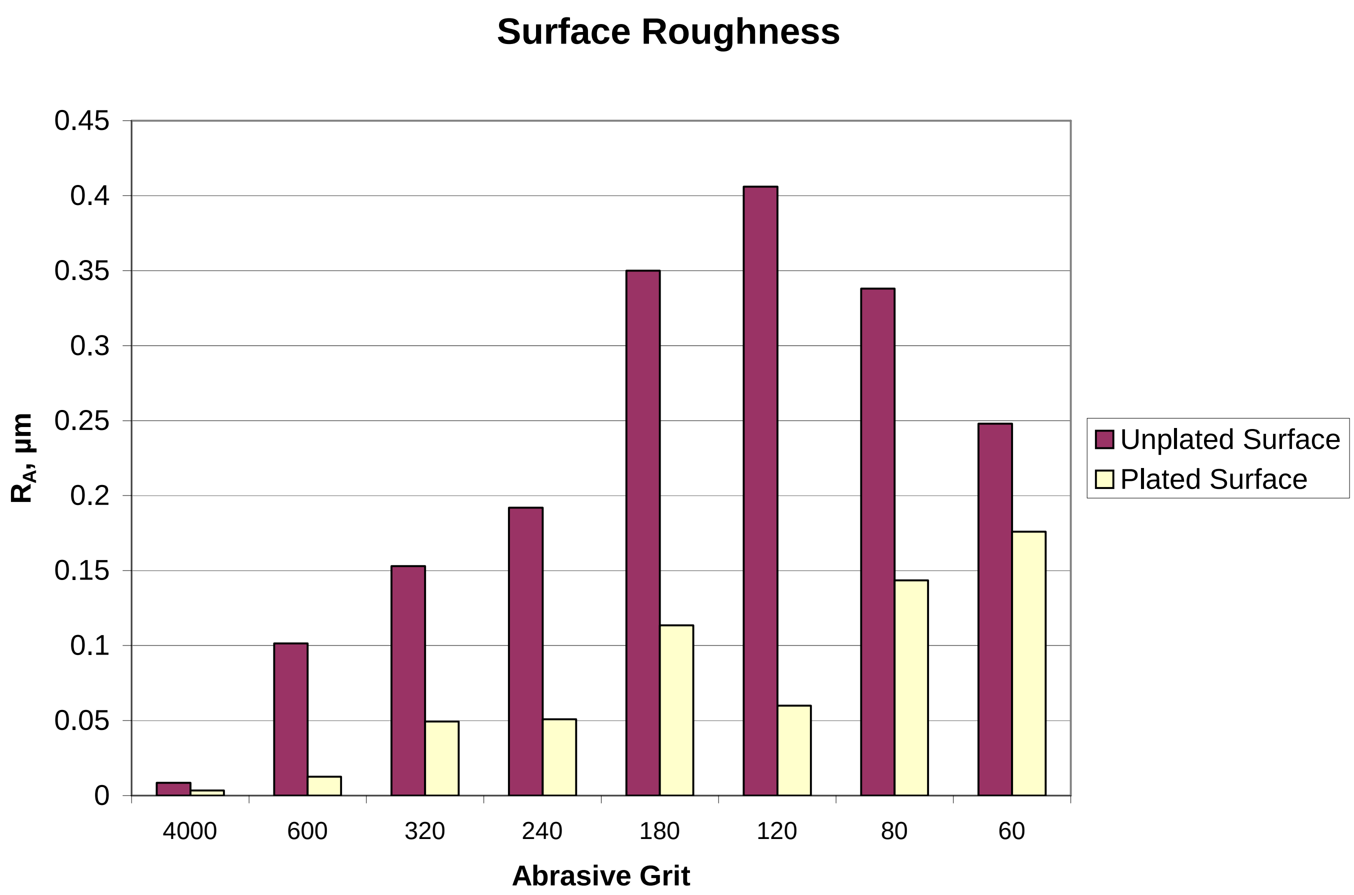
- Initial surface finish in as-received spray holes is R_A ca. 0.5 µm
- In bench-scale tests, the best final spray hole R_A was ca. 0.2 µm
- In bench-scale plating tests on flats with different R_A values, the post-plating R_A was always lower than the initial R_A



- Orifice interior micrographs before (L) and after (R) 15 min EN plating; image size 100 µm across



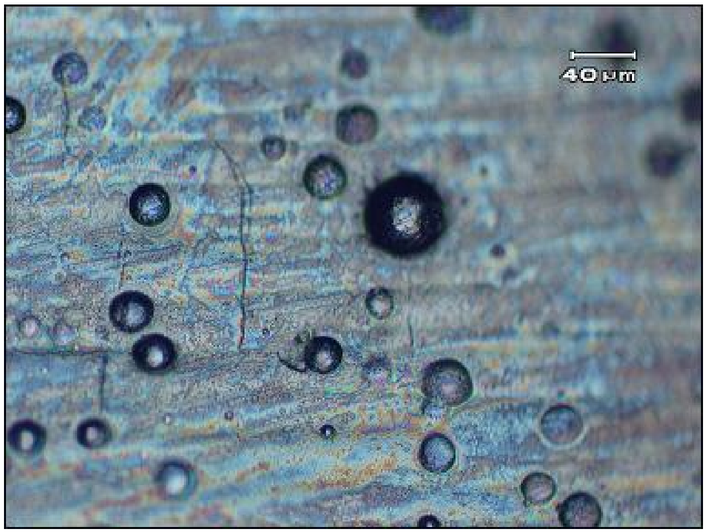
Results: Surface Finish (cont'd)



- **Smoother surfaces should lead to higher discharge coefficients**

Results: Surface Finish (cont'd)

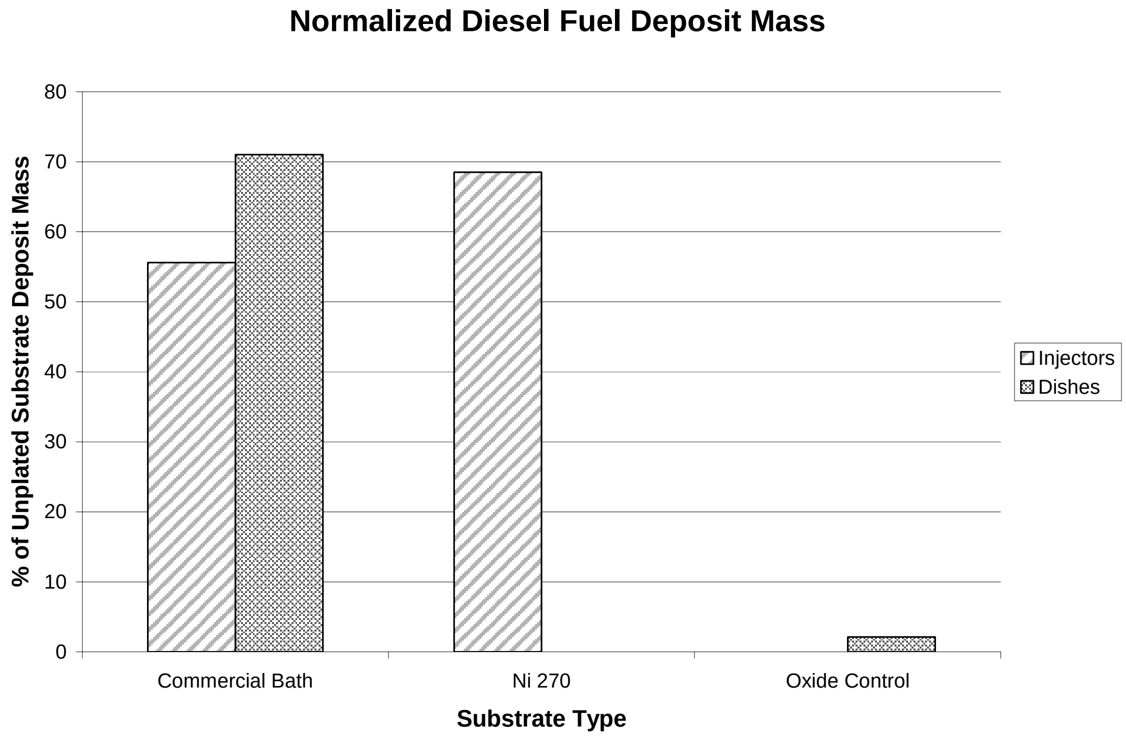
- **Initially there were problems with the commercial-scale coatings, caused by accumulation of hydrogen bubbles on the surface**



- **These were solved in the most recent set of coatings**

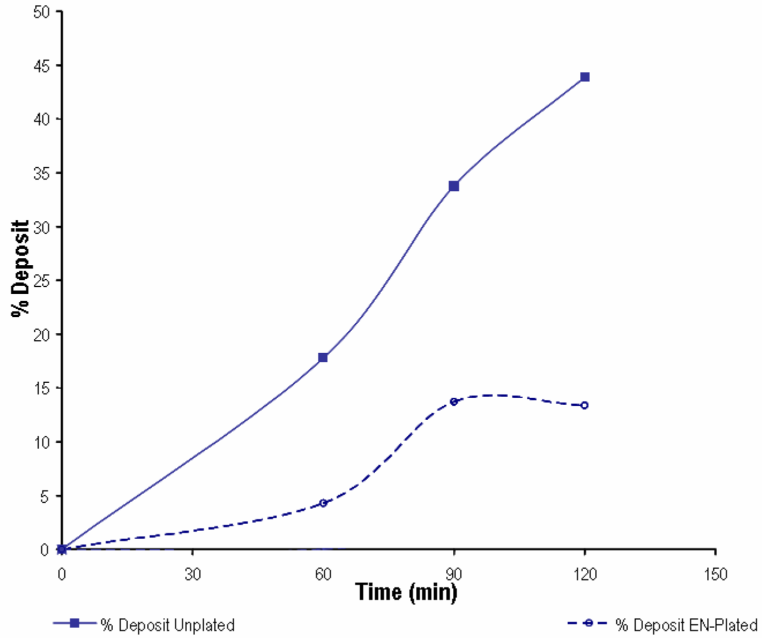
Results: Combustion Deposit Resistance

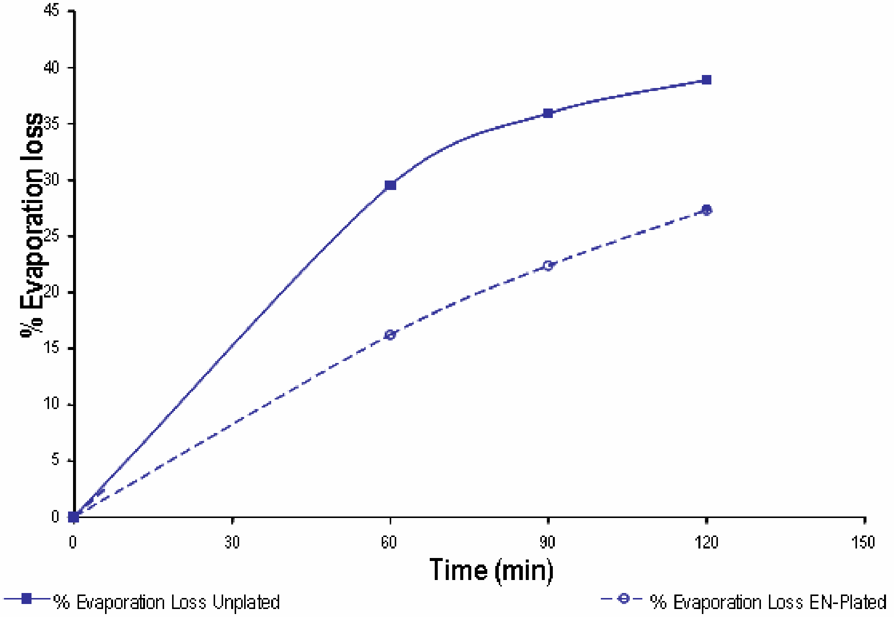
- **In bench tests, the commercial EN plating bath appears to be less prone to deposit formation than steel**



Results: Combustion Deposit Resistance (cont'd)

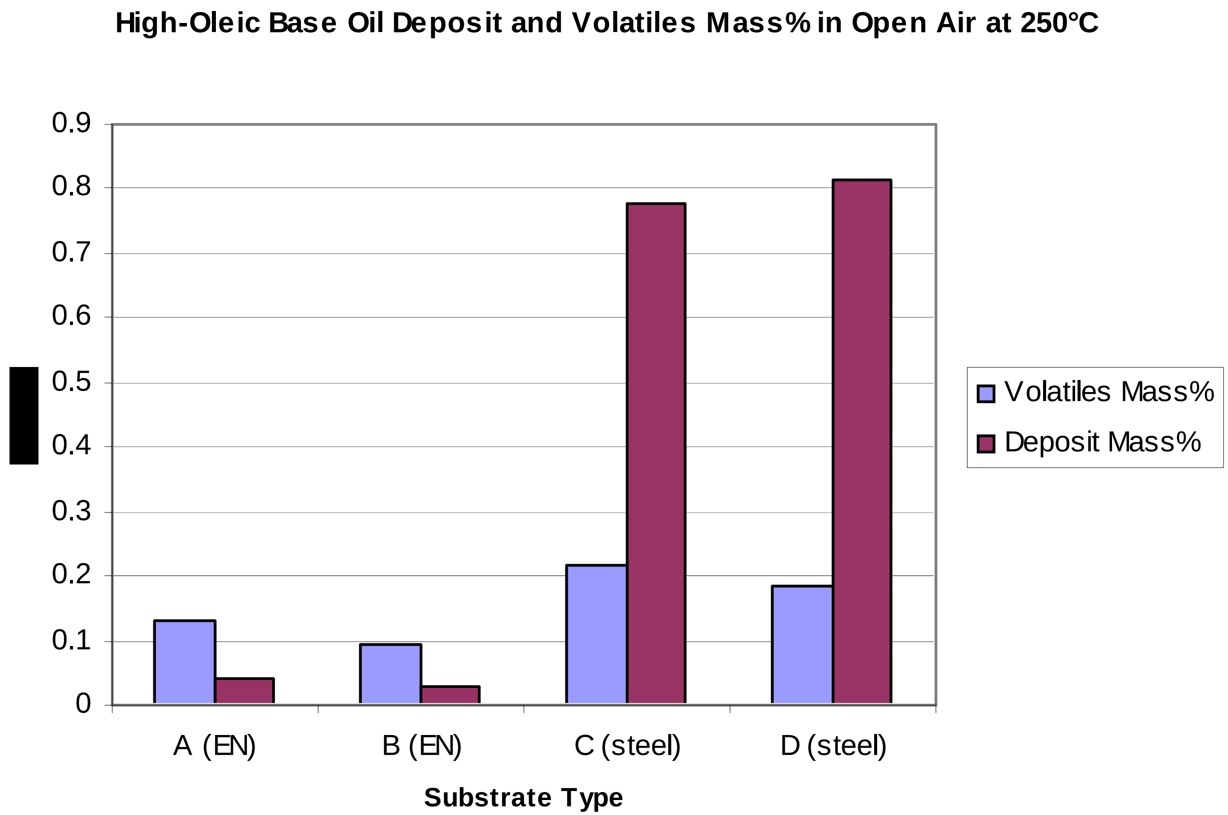
- **PSMO tests are also encouraging**





Results: Combustion Deposit Resistance (cont'd)

- **Further bench tests at 250°C with high-oleic sunflower oil show even greater differences between steel and EN**



Conclusions & Future Work

- **Economical fabrication of fuel injector nozzles with orifice sizes 50-75 µm via EN plating has been demonstrated**
- **Further work is in progress or planned:**
  - Spray visualization and LD engine testing
  - Impact resistance tests on coated needle seats
  - Spray tests with alternative fuels